

# Estimation of isotropization time ( $\tau_{\text{iso}}$ ) of QGP from direct photons

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## Abstract

We calculate transverse momentum distribution of direct photons from various sources by taking into account the initial state momentum anisotropy of quark gluon plasma (QGP). The total photon yield is then compared with the recent measurement of photon transverse momentum distribution by the PHENIX collaboration. It is also demonstrated that the presence of such an anisotropy can describe the PHENIX photon data better than the isotropic case in the present model. We show that the isotropization time thus extracted lies within the range  $1.5 \geq \tau_{\text{iso}} \geq 0.5$  fm/c for the initial condition used here.

**Keywords:** anisotropy, QGP

## 1. Introduction

The primary goal of relativistic heavy ion collisions is to create a new state of matter, called quark gluon plasma and to study its properties through various indirect probes. Out of all the properties of the QGP, the most difficult problem lies in the determination of isotropization and thermalization time scales ( $\tau_{\text{iso}}$  and  $\tau_{\text{therm}}$ ). Studies on elliptic flow (upto about  $p_T \sim 1.5 - 2$  GeV) using ideal hydrodynamics indicate that the matter produced in such collisions becomes isotropic with  $\tau_{\text{iso}} \sim 0.6$  fm/c (1). On the other hand, using second order transport coefficients with conformal symmetry it is found that the isotropization/thermalization time has sizable uncertainties (2). Consequently, there are uncertainties in the initial temperature as well. Electromagnetic probes have been proposed to be one of the most promising tools to characterize the initial state of the collisions (3, 4). Because of the very nature of their interactions with the constituents of the system they tend to leave the system without much change of their energy and momentum. In fact, photons (dilepton as well) can be used to determine the initial temperature, or equivalently the equilibration time.

It is to be noted that while estimating photons from QGP (5, 6, 7), it is assumed that the matter formed in the relativistic heavy ion collisions is in thermal equilibrium. The measurement of elliptic flow parameter and its theoretical explanation also support this assumption. On the contrary, perturbative estimation suggests the slower thermalization of QGP (8). However, recent hydrodynamical studies (2) have shown that due to the poor knowledge of the initial conditions there is a sizable amount of uncertainty in the estimate of thermalization or isotropization time. In view of the absence of a theoretical proof behind the rapid thermalization and the uncertainties in the hydrodynamical fits of experimental data, such an assumption may not be justified. Hence in stead of equating the thermalization/isotropization time to the QGP formation time, in this work, we will introduce an intermediate time scale (isotropization time,  $\tau_{\text{iso}}$ ) to study the effects of early time momentum-space anisotropy on the total photon yield and compare it with the PHENIX photon data (9, 10, 11). Recently, it has been shown in Ref. (12) that for fixed initial conditions, the introduction of a pre-equilibrium momentum-space anisotropy enhances high energy dileptons by an order of magnitude. In case of photon transverse momentum distribution similar results have been reported for various evolution scenarios (13).

The plan of the paper is the following. In the next section we will discuss the mechanisms of photon production from various possible sources and the space-time evolution of the matter very briefly. Section 3 is devoted to describe the results for various initial conditions and we summarize in section 4.

## 2. Formalism

### 2.1. Photon rate: Anisotropic QGP

The lowest order processes for photon emission from QGP are the Compton ( $q(\bar{q})g \rightarrow q(\bar{q})\gamma$ ) and the annihilation ( $q\bar{q} \rightarrow g\gamma$ ) processes. The rate of photon production from anisotropic plasma due to these processes has been calculated in Ref. (14). The soft contribution is calculated by evaluating the photon polarization tensor for an oblate momentum-space anisotropy of the system where the cut-off scale is fixed at  $k_c \sim \sqrt{g}p_{hard}$ . Here  $p_{hard}$  is a hard-momentum scale that appears in the distribution functions. The differential photon production rate for  $1 + 2 \rightarrow 3 + \gamma$  processes in an anisotropic medium is given by (14):

$$\begin{aligned} E \frac{dN}{d^4x d^3p} &= \frac{N}{2(2\pi)^3} \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} f_1(\mathbf{p}_1, p_{hard}, \xi) f_2(\mathbf{p}_2, p_{hard}, \xi) \\ &\times (2\pi)^4 \delta(p_1 + p_2 - p_3 - p) |\mathcal{M}|^2 [1 \pm f_3(\mathbf{p}_3, p_{hard}, \xi)] \end{aligned} \quad (1)$$

where,  $|\mathcal{M}|^2$  represents the spin averaged matrix element squared for one of those processes which contributes to the photon rate and  $N$  is the degeneracy factor of the corresponding process.  $\xi$  is a parameter controlling the strength of the anisotropy with  $\xi > -1$ .  $f_1$ ,  $f_2$  and  $f_3$  are the anisotropic distribution functions of the medium partons. Here it is assumed that the infrared singularities can be shielded by the thermal masses for the participating partons. This is a good approximation at short times compared to the time scale when plasma instabilities start to play an important role. The anisotropic distribution function can be obtained (15) by squeezing or stretching an arbitrary isotropic distribution function along the preferred direction in momentum space,  $f_i(\mathbf{k}, \xi, p_{hard}) = f_i^{iso}(\sqrt{\mathbf{k}^2 + \xi(\mathbf{k} \cdot \mathbf{n})^2}, p_{hard})$ , where  $\mathbf{n}$  is the direction of anisotropy. It is important to notice that  $\xi > 0$  corresponds to a contraction of the distribution function in the direction of anisotropy and  $-1 < \xi < 0$  corresponds to a stretching in the direction of anisotropy. In the context of relativistic heavy ion collisions, one can identify the direction of anisotropy with the beam axis along which the system expands initially. The hard momentum scale  $p_{hard}$  is directly related to the average momentum of the partons. In the case of an isotropic QGP,  $p_{hard}$  can be identified with the plasma temperature ( $T$ ).

### 2.2. Photon rate : Isotropic case

As mentioned earlier the QGP evolves hydrodynamically from  $\tau_{iso}$  onwards. In such case the distribution functions become Fermi-Dirac or Bose-Einstein distributions. The photon emission rate, in isotropic case, from Compton ( $q(\bar{q})g \rightarrow q(\bar{q})\gamma$ ) and annihilation ( $q\bar{q} \rightarrow g\gamma$ ) processes has been calculated from the imaginary part of the photon self-energy by Kapusta et al. (16) in the 1-loop approximation. However, it has been shown by Auranche et al. (17) that the two loop contribution is of the same order as the one loop due to the shielding of infra-red singularities. The complete calculation upto two loop was done by Arnold et al. (18). In this paper we have calculated the photon production rate from hot hadronic matter. We follow the calculations done in Ref. (19) where convenient parameterizations have been given for the reactions considered. These parameterizations will be used while doing the space-time evolution to calculate the photon yield from meson-meson reactions. The photon emission rate (static) from reactions of the type  $BM \rightarrow B\gamma$  ( $B$  denotes baryon) has been calculated in Ref. (20). It is shown that this contribution is not negligible compared to that meson-meson reactions. To evaluate photon rate due to nucleon (and antinucleon) scattering from  $\pi$ ,  $\rho$ ,  $\omega$ ,  $\eta$  and  $a_1$  mesons in the thermal bath we use the phenomenological interactions described in Ref. (20). Besides the thermal photons from QGP and hadronic matter we also calculate photons from initial hard scattering from the reaction of the type  $h_A h_B \rightarrow \gamma X$  using perturbative QCD. We include the transverse momentum broadening in the initial state partons (21, 22).

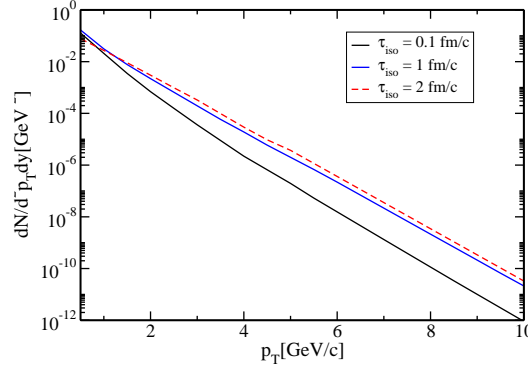


Figure 1: (Color online) Medium photon spectrum,  $dN/d^2p_T dy$ , at  $y = 0$  for the *free-streaming interpolating* model ( $\delta = 2$ ) for three different values of isotropization time,  $\tau_{iso}$ , with initial conditions,  $T_i = 440$  GeV and  $\tau_i = 0.1$  fm/c.

### 2.3. Space-time evolution

The expected total photon rate must be convoluted with the space-time evolution of the fireball. The system evolves anisotropically from  $\tau_i$  to  $\tau_{iso}$  where one needs to know the time dependence of  $p_{hard}$  and  $\xi$ . We have used a phenomenological model (12, 13) to describe the time dependence of  $p_{hard}$  and  $\xi$ . In the frame work of this model,  $\xi = 0$  at  $\tau = \tau_i$  and it grows with time ( $\tau$ ) and reaches maximum at  $\tau = \tau_{iso}$ , after that  $\xi$  decreases to zero at  $\tau \gg \tau_{iso}$ . We shall follow the work of Ref. (12, 13) to evaluate the  $p_T$  distribution of photons from the first few Fermi of the plasma evolution. In our calculation, we assume a first-order phase transition beginning at the time  $\tau_c(p_{hard}(\tau_c) = T_c)$  and ending at  $\tau_H = r_d \tau_c$  where  $r_d = g_Q/g_H$  is the ratio of the degrees of freedom in the two (QGP phase and hadronic phase) phases. Therefore, the total thermal photon yield, arising from the present scenario is given by,

$$\frac{dN}{d^2p_T dy} = \left[ \int d^4x E \frac{dR}{d^3p} \right]_{aniso} + \left[ \int d^4x E \frac{dR}{d^3p} \right]_{hydro}, \quad (2)$$

where the first term denotes the contribution from the anisotropic QGP phase and the second term represents the contributions evaluated in ideal hydrodynamics scenario.

### 3. Results

We have considered the initial condition,  $T_i = 440$  MeV,  $\tau_i = 0.1$  fm/c and *free-streaming interpolating* model ( $\delta = 2$ ) (13, 23) for the pre-equilibrium evolution. In this initial condition the maximum value of  $\xi$  will be  $\sim 70$  at  $\tau = \tau_{iso}$ . In Fig. (1) we present the photon yield due to Compton and annihilation processes in the mid rapidity ( $\theta_\gamma = \pi/2$ ,  $\theta_\gamma$  being the angle between the photon momentum and the anisotropy direction) as a function of photon transverse momentum. In estimating this result, we have used  $\alpha_s = 0.3$ . Different lines in Fig. 1 correspond to different isotropization times,  $\tau_{iso}$ . We clearly observe enhancement of photon yield when  $\tau_{iso} > \tau_i$ . The enhancement of photon yield in the transverse directions ( $y = 0$ ) is due to the fact that momentum-space anisotropy enhances the density of plasma partons moving at the mid rapidity (13). To show that the presence of initial state momentum anisotropy and the importance of the contribution from baryon-meson reactions we plot the the total photon yield assuming hydrodynamic evolution from the very begining as well as with finite  $\tau_{iso}$  (right panel describes the total contribution with and without the initial state momentum space anisotropy only for  $\tau_{iso} = 1$  fm/c) in Fig. (2). It is clearly seen that some amount of anisotropy is needed to reproduce the data. We note that the value of  $\tau_{iso}$  needed to describe the data also lies in the range  $1.5 \text{ fm/c} \geq \tau_{iso} \geq 0.5 \text{ fm/c}$  for both values of the transition temperatures.

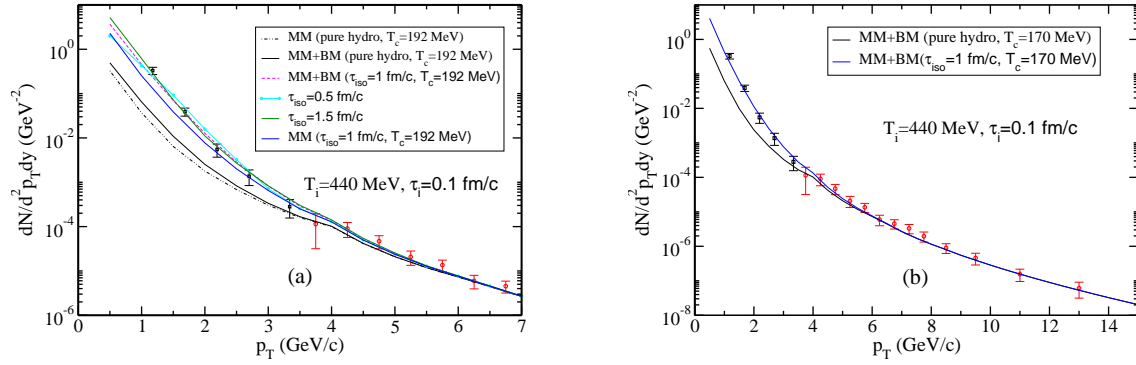


Figure 2: (Color online) Photon  $p_T$  distributions at RHIC energies with initial condition  $T_i = 440$  GeV, for (a)  $T_c = 192$  MeV and (b) 170 MeV.

#### 4. Conclusion

To summarize, we have calculated total single photon transverse momentum distributions by taking into account the effects of the pre-equilibrium momentum space anisotropy of the QGP and late stage transverse expansion on photons from hadronic matter with various initial conditions. To describe space-time evolution in the very early stage we have used the phenomenological model described in Ref. (12) for the time dependence of the hard momentum scale ( $p_{hard}$ ) and plasma anisotropy parameter ( $\xi$ ). To calculate the hard photon contributions we include the transverse momentum broadening in the initial hard scattering. The total photon yield is then compared with the PHENIX photon data. Within the ambit of the present model it is shown that the data can be described quite well if  $\tau_{iso}$  is in the range of 0.5 - 1.5 fm/c for all the combinations of initial conditions and transition temperatures considered here. It is to be noted that the apparent hump observed in all the figures (except Fig.(5)) needs to be understood and we wish to discuss it in a subsequent paper.

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